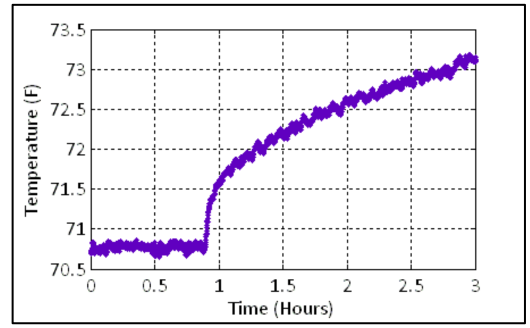
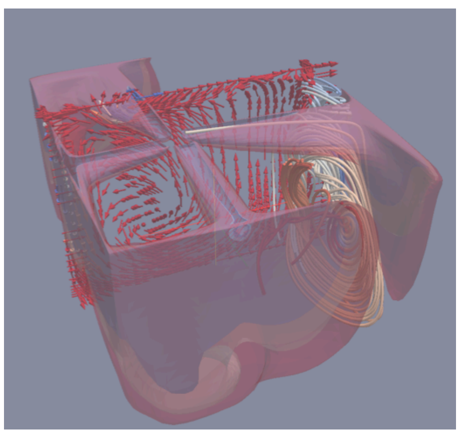
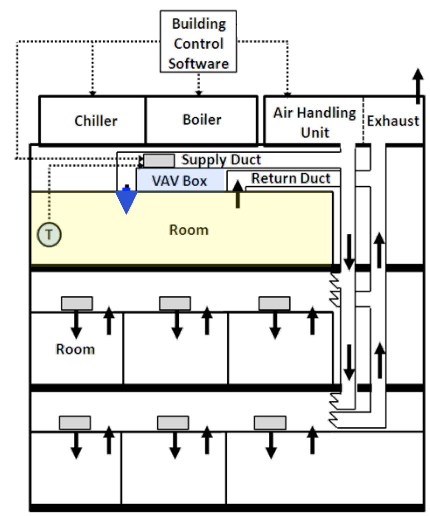


Software-Based Building Airflow Analysis Tool for Enabling HVAC Energy Use Savings in Commercial Buildings**

Don Wroblewski, P.E.
Boston University
dew11@bu.edu



** A work in progress



LBNL EETD Seminar 3/8/13

OUTLINE

- Introduction
- Motivation
- Solution
- Proof of Concept
- Commercialization

ACKNOWLEDGMENTS

CO-CONSPIRATOR

Mike Gevelber
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PECI

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BuildingIQ

KGS Systems

Kimberly-Clark Corporation

Sebesta Blomberg

State University of New York

GreenerU

Rockport Capital

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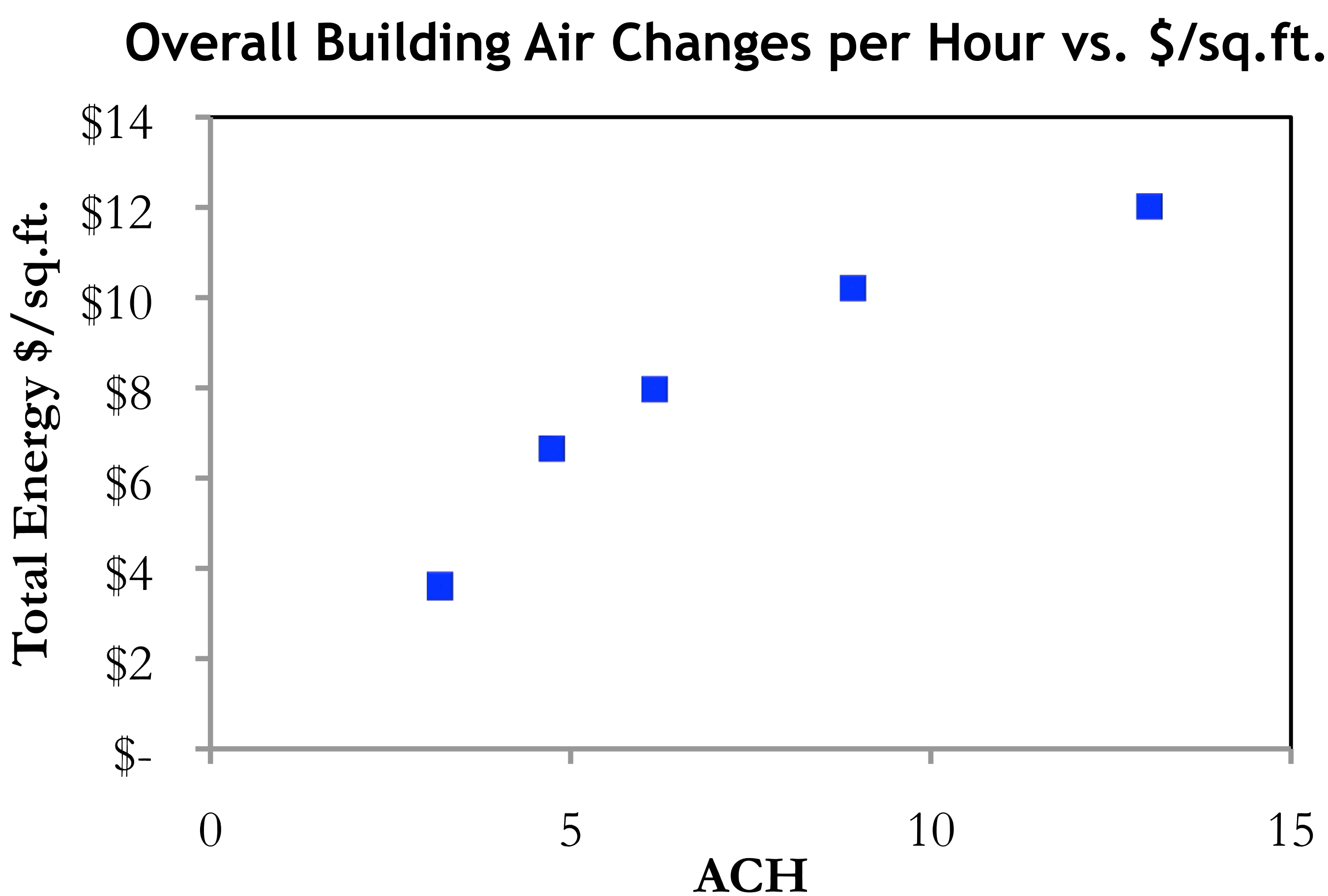
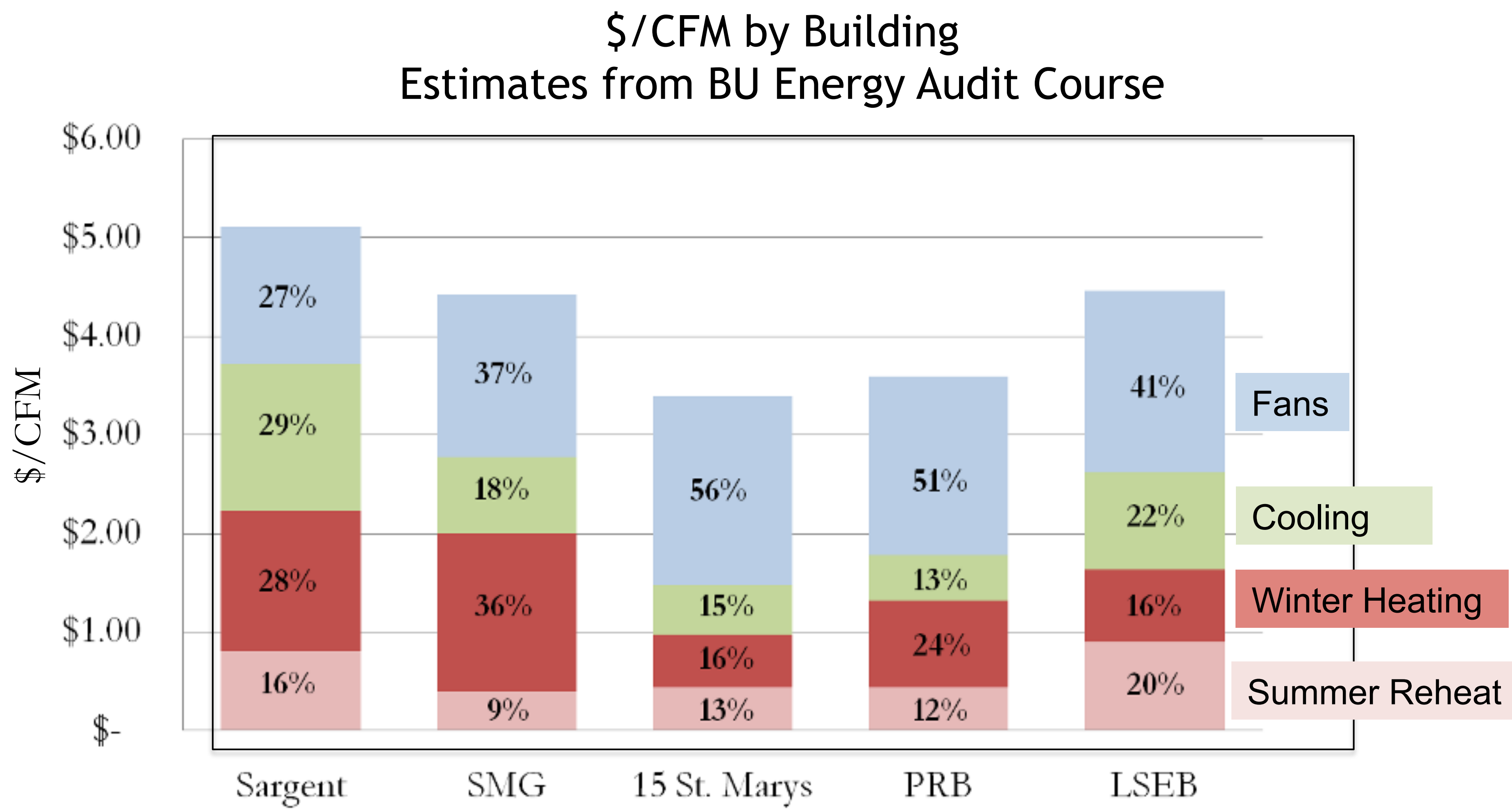
BU ENERGY AUDIT COURSE

Building Energy Costs Scale with Airflow rate



FAN ENERGY IS SIGNIFICANT PART OF $/CFM



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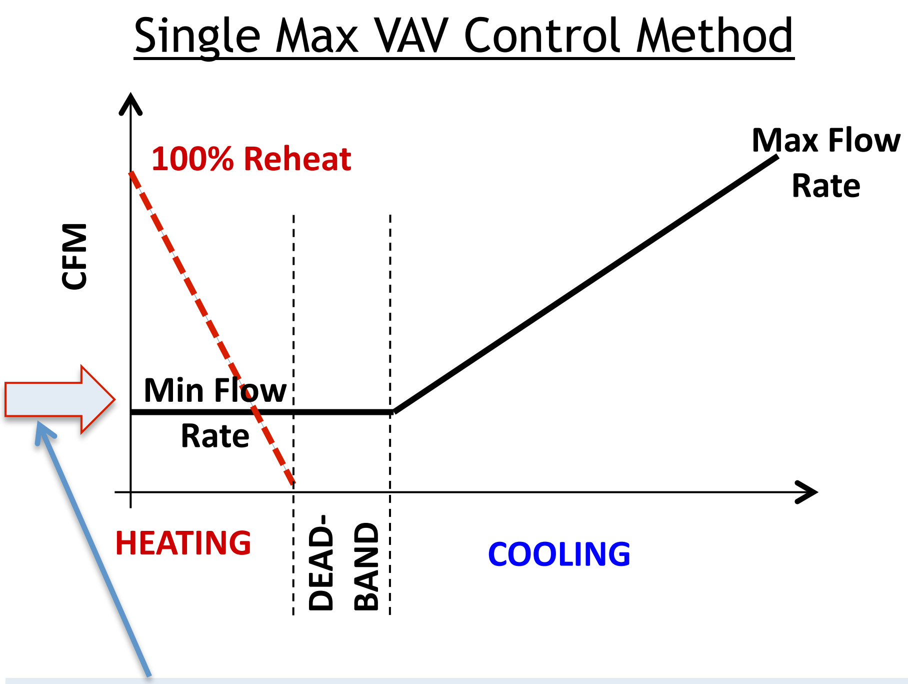
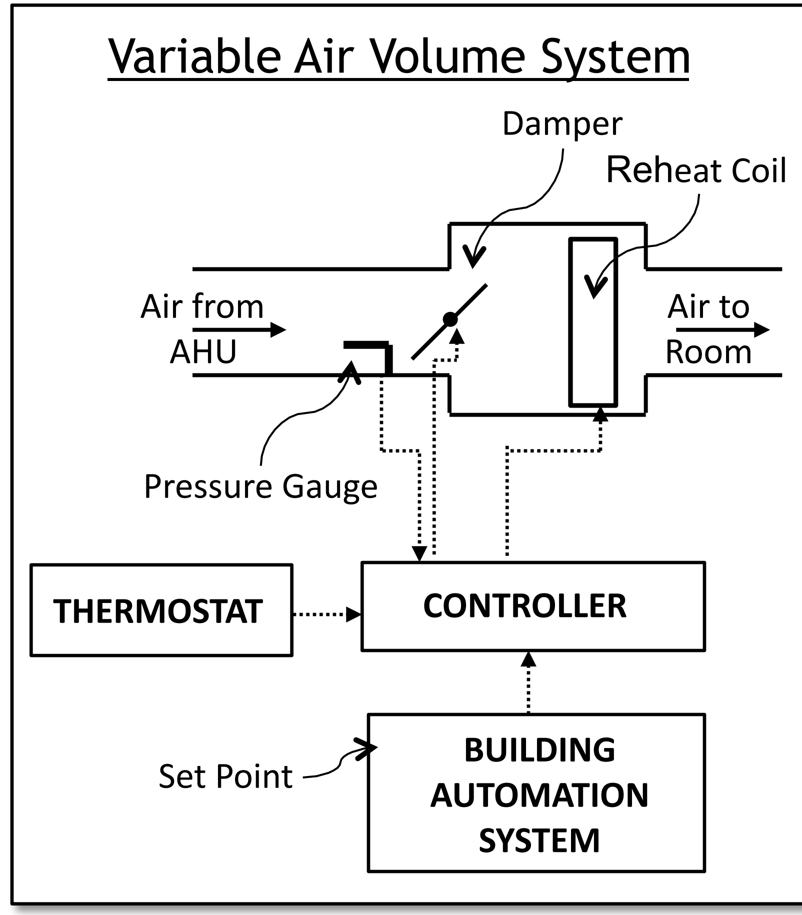
REDUCE MINIMUM VAV AIRFLOW SETTING



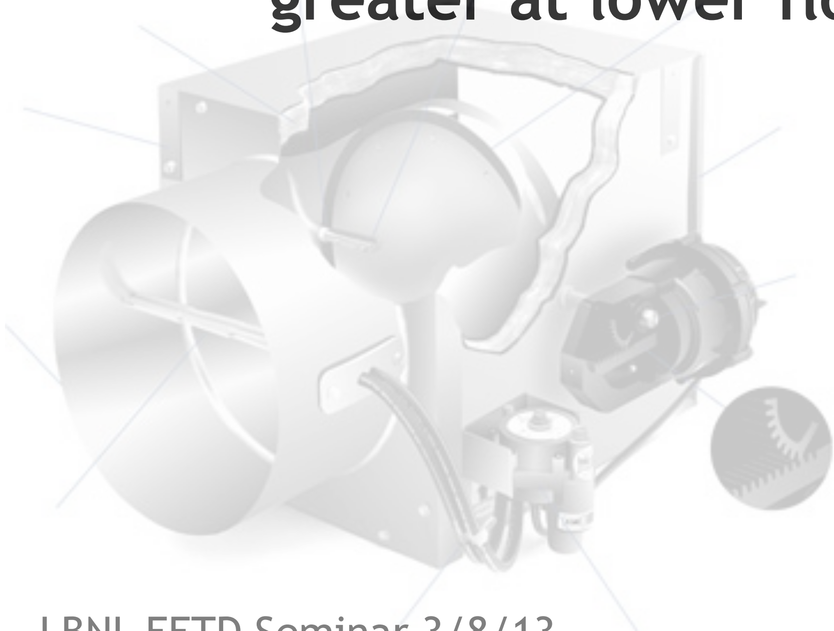


Minimum Air Flow typically set higher than code requirements*

***Advanced VAV System Design Guide*, 2003**

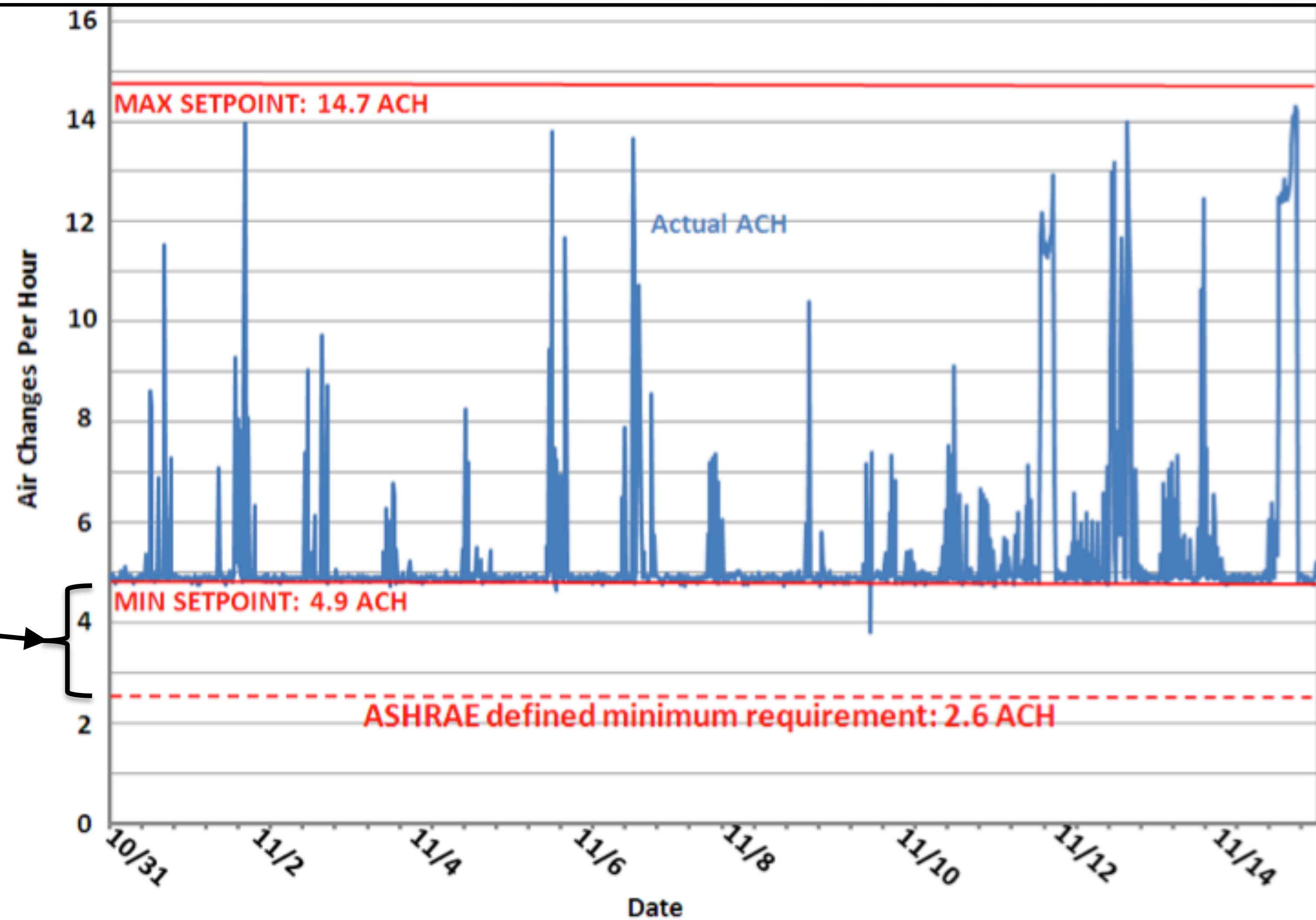
REDUCE MINIMUM VAV AIRFLOW SETTING

- Blanc, 2007: VAV controllable down to 10% of design flow
- Arens, 2011: 24-30% HVAC energy savings by reducing minimum from 30 to 10% of max.
- Fisk, et al, 1997: Air Change Effectiveness is greater at lower flow rates



MOTIVATION

POTENTIAL FOR SAVINGS



Minimum Air Flow set 38% Higher Ventilation Requirement

MOTIVATION

SETTING MINIMUM AIR FLOWS: NEW APPROACH NEEDED

Manually Measuring Airflow

Labor Intensive

Time Consuming

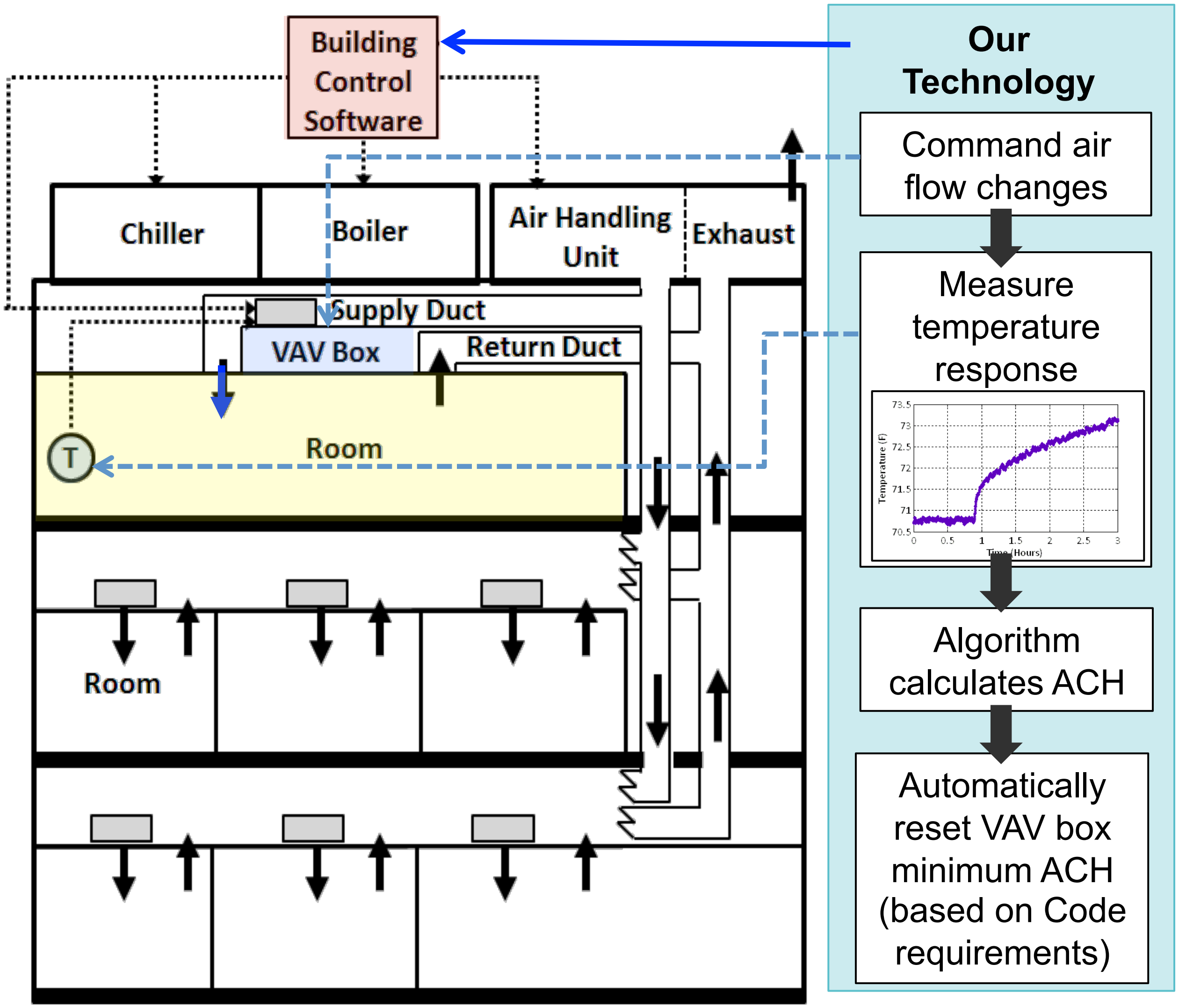
Only first step in process

Ideally measure ACH

OBJECTIVE: Develop more cost effective way to measure ACH and reset minimums

SOLUTION

OUR SYSTEM ID SOFTWARE APPROACH



Software approach enables fully integrated solutions

Room-by-room results aggregable for building level savings

Enables monitoring & diagnostics

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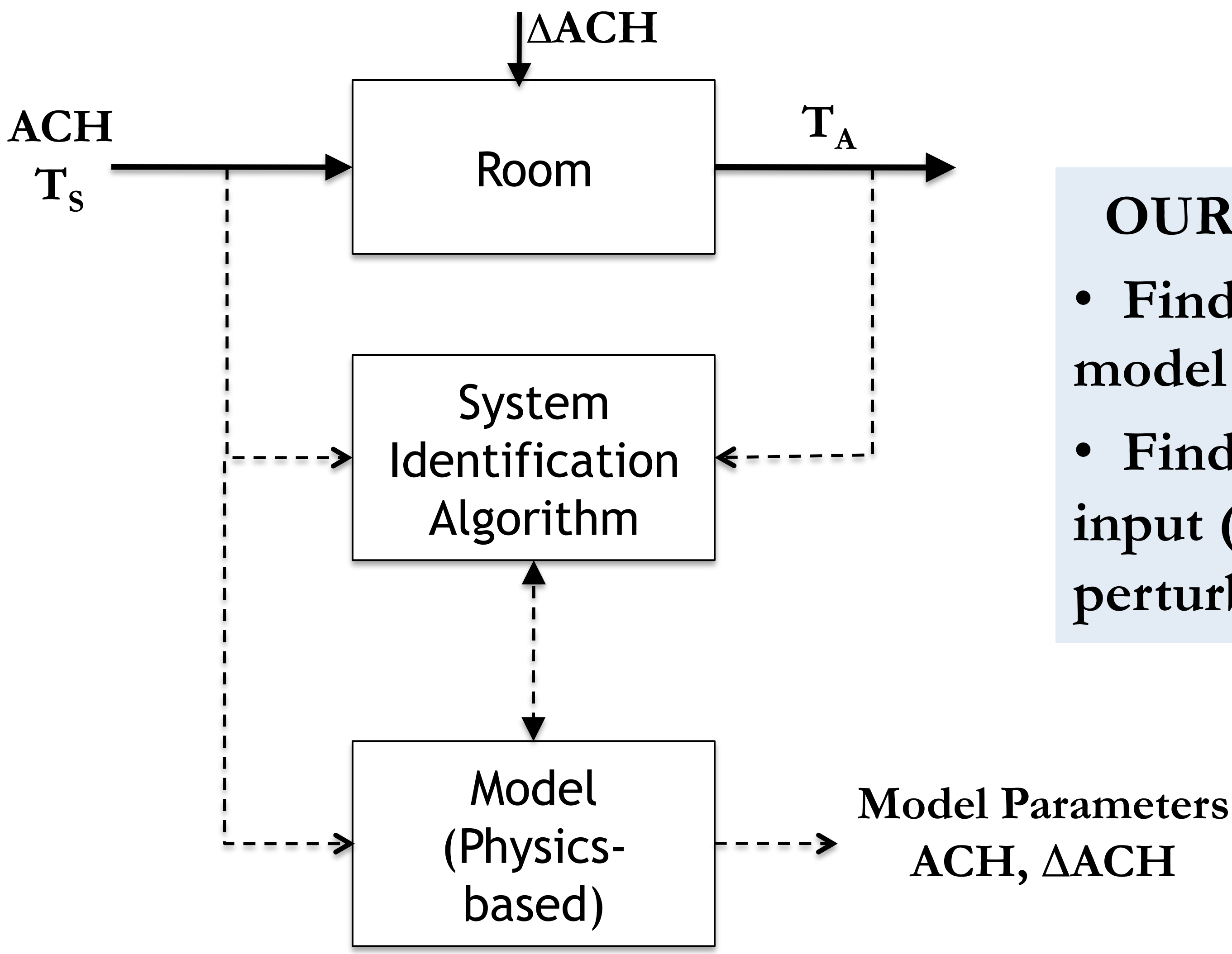
SYSTEM IDENTIFICATION



OUR APPROACH

- **Find unknown model parameters**
- **Find unknown input (ACH) and perturbation (ΔACH)**

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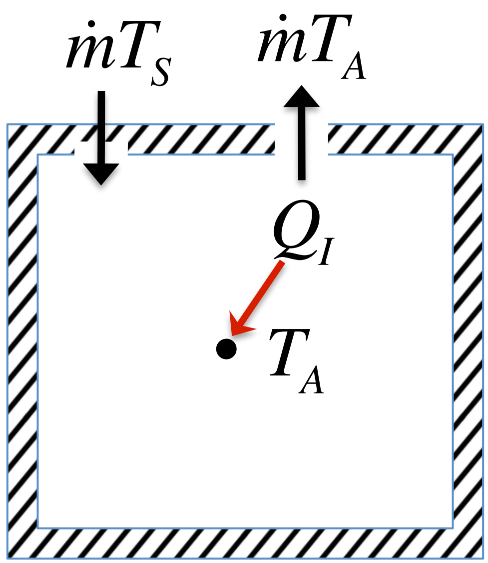
1st ORDER SI MODEL

Fully Insulated Interior Room



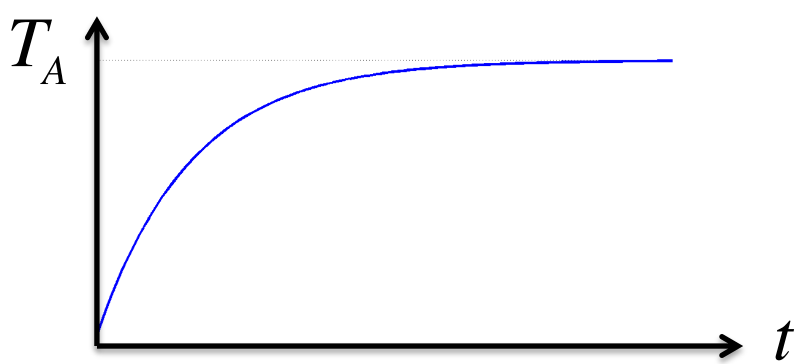
$$C_A \frac{dT_A}{dt} = \dot{m}c_p(T_S - T_A) + Q_I$$

$$T_A = T_{A,SS} + \alpha e^{\lambda t}$$

1st Order Response

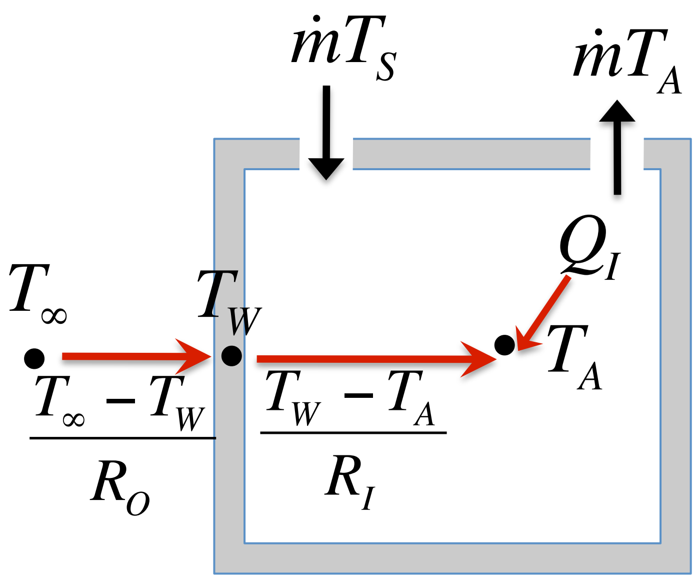
$$\tau = -\frac{1}{\lambda} = \frac{1}{ACH}$$

(Air Change Rate)



SECOND ORDER MODEL

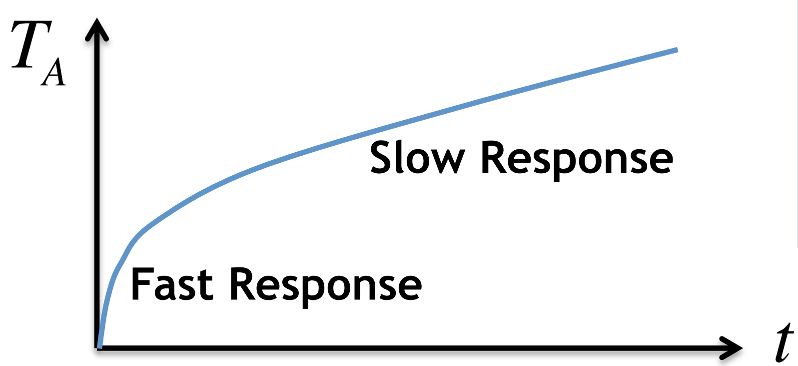
Heat transfer: air ⟷ walls



$$C_A \frac{dT_A}{dt} = \dot{m}c_p(T_S - T_A) + Q_I + \boxed{\frac{T_W - T_A}{R_I}}$$

$$C_W \frac{dT_W}{dt} = \frac{T_\infty - T_W}{R_O} + \boxed{\frac{T_A - T_W}{R_I}}$$

$$T_A = T_{A,SS} + \alpha_1 e^{\lambda_1 t} + \alpha_2 e^{\lambda_2 t}$$



2nd Order Response with fast and slow time constants

$$\lambda_1, \lambda_2 = fn\left(ACH, C_A, C_W, R_O, R_I\right)$$

SOLUTION

TRANSFER FUNCTION APPROACH: LAPLACE TRANSFORMS

Impose Step change in ACH

$$T_A = T_{A,SS} + \alpha_1 e^{\lambda_1 t} + \alpha_2 e^{\lambda_2 t}$$

$$\overline{T}_A(s) \equiv \int_0^\infty e^{-st} T_A(t)\,dt$$

Transfer Function

$$\overline{T}_A(s) = \boxed{\frac{\left(T_S - \overline{T}_0\right)\left(s + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right)}{(s-\lambda_1)(s-\lambda_2)}\frac{1}{s}}\,\Delta ACH$$

$$\lambda = -\frac{1}{2}\left(ACH + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right) \pm \frac{1}{2}\sqrt{\left(ACH + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right)^2 - 4\left(\frac{ACH}{R_I C_W} + \frac{ACH}{R_O C_W} + \frac{1}{R_I C_A R_O C_W}\right)}$$

Poles=1/time constant

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FIRST ORDER ASYMPTOPTIC SOLUTION

$$C_W >> C_A$$

Fast Response

$$C_A \frac{dT_A}{dt} = \dot{m}c_p(T_S - T_A) + Q_I + \frac{T_W - T_A}{R_I}$$

$$\hat{\lambda}_1 = ACH + \frac{1}{R_I C_A}$$

Slow Response

$$0 = \dot{m}c_p(T_S - T_A) + Q_I + \frac{T_W - T_A}{R_I}$$

$$C_W \frac{dT_W}{dt} = \frac{T_\infty - T_W}{R_O} + \frac{T_A - T_W}{R_I}$$

$$\widehat{\lambda}_2 = \frac{1}{R_I C_W}\left[1 - \left\{\left(ACH + \frac{1}{R_I C_A}\right) R_I C_A\right\}^{-1}\right] + \frac{1}{R_O C_W}$$

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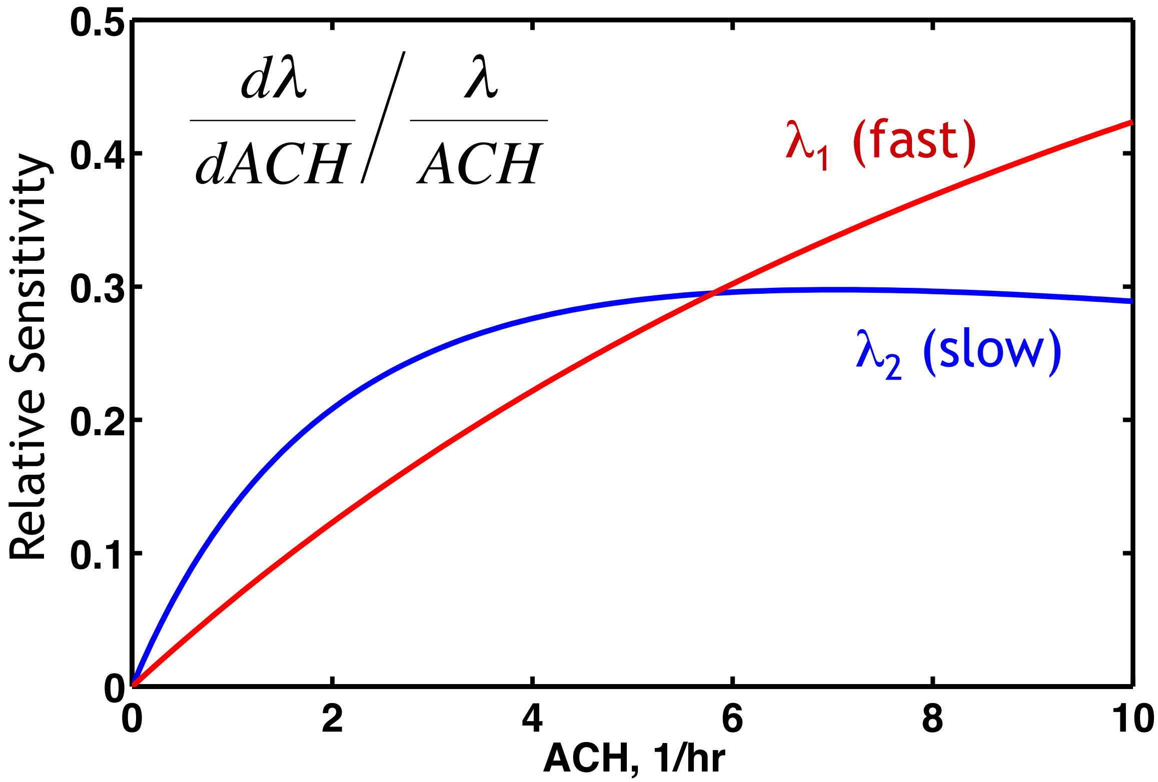
POLE SENSITIVITY TO ACH

Relative Sensitivity of λ_1 and λ_2



Relative sensitivity of slow pole is better than fast pole for ACH<6

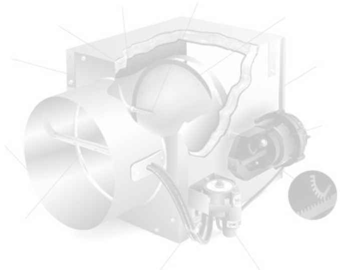
$$\lambda = -\frac{1}{2}\left(ACH + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right) \pm \frac{1}{2}\sqrt{\left(ACH + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right)^2 - 4\left(\frac{ACH}{R_I C_W} + \frac{ACH}{R_O C_W} + \frac{1}{R_I C_A R_O C_W}\right)}$$

SOLUTION

SUMMARY OF SI APPROACH

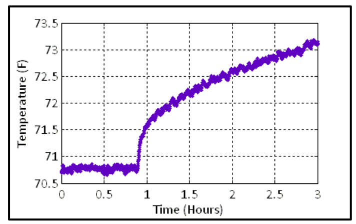
Change VAV box flow rate (ACH)

↓



Fit second order equation to temperature response (e.g., NLLS)

$$T_A = T_{A,SS} + \alpha_1 e^{-\lambda_1 t} + \alpha_2 e^{-\lambda_{21} t}$$



↓

Extract ACH from fit constants

$$\lambda = -\frac{1}{2}\left(ACR + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right) \pm \frac{1}{2}\sqrt{\left(ACR + \frac{1}{R_I C_A} + \frac{1}{R_I C_W} + \frac{1}{R_O C_W}\right)^2 - 4\left(\frac{ACR}{R_I C_W} + \frac{ACR}{R_O C_W} + \frac{1}{R_I C_A R_O C_W}\right)}$$

CHALLENGE:

Design experimental protocol to facilitate ACH extraction with highest accuracy

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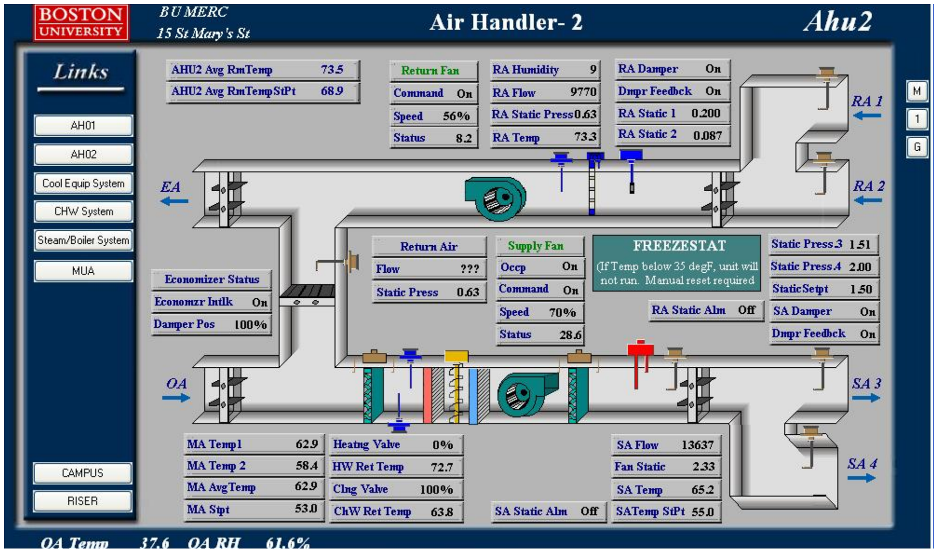
EXPERIMENTS AT B.U.



Schneider Electric Continuum Workstation

TC-instrumented Room

- **Occupied zone**
- **Dummy t'stat**
- **Wall**
- **Exhaust & Supply Vents**
- **Primary air zone**

Balometer for initial and final flow rates

PROOF OF CONCEPT

EXPERIMENTS AT B.U.

Building	Room Number	Room Type	Floor Area (ft^2)	No. VAV Boxes	No. Tests Run
15 St Mary's Street	136	Office	150	1	50
15 St Mary's Street	150	Classroom	698	2	10
15 St Mary's Street	124	Computer Lab	1261	2	5
15 St Mary's Street	131	Office	176	1	10
Photonics	B11C	Laboratory	618	3	5
Photonics	B14	Office	158	1	20
Photonics	736A	Lab Office	100	1	10

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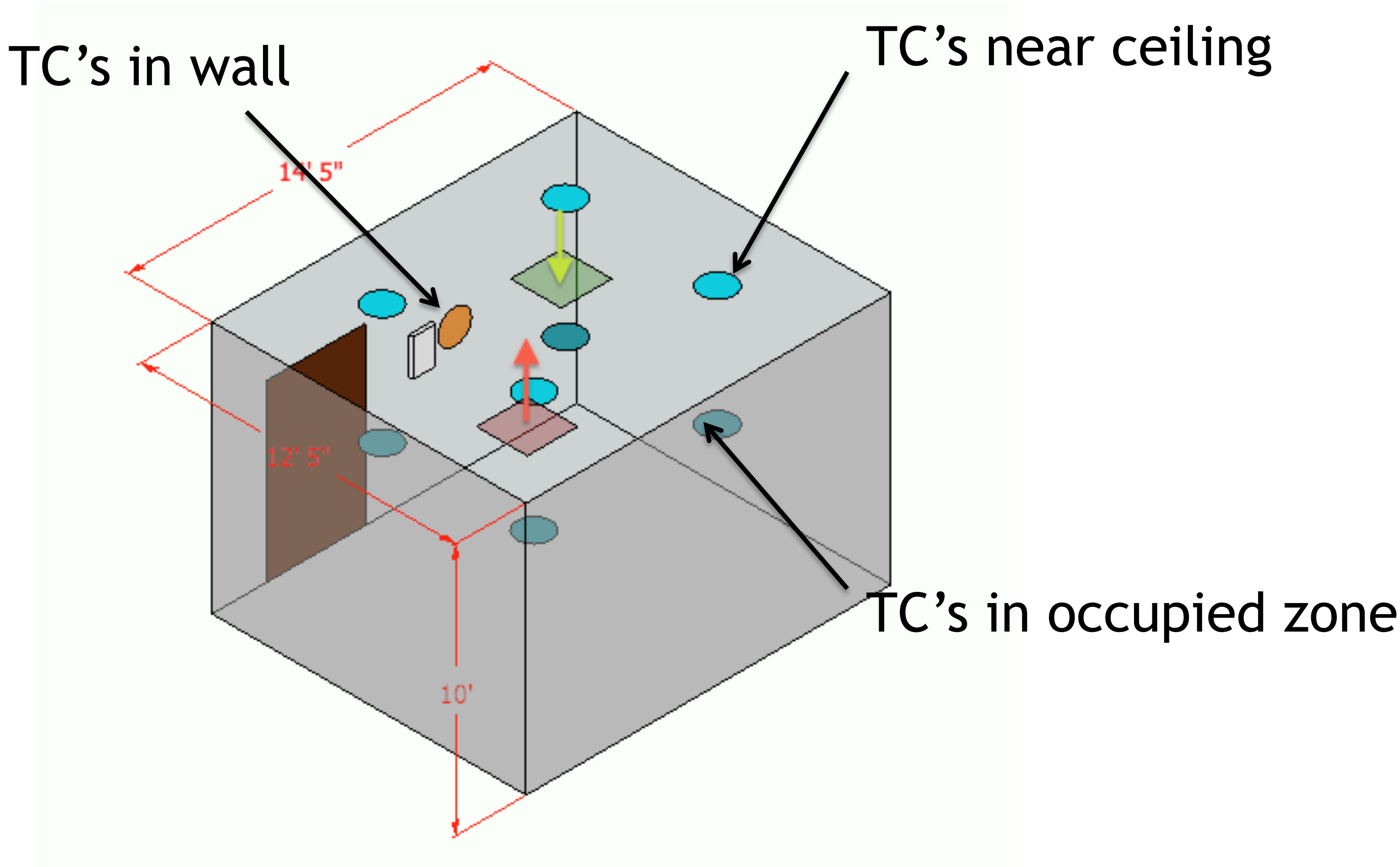
RM 136 15 ST MARYS



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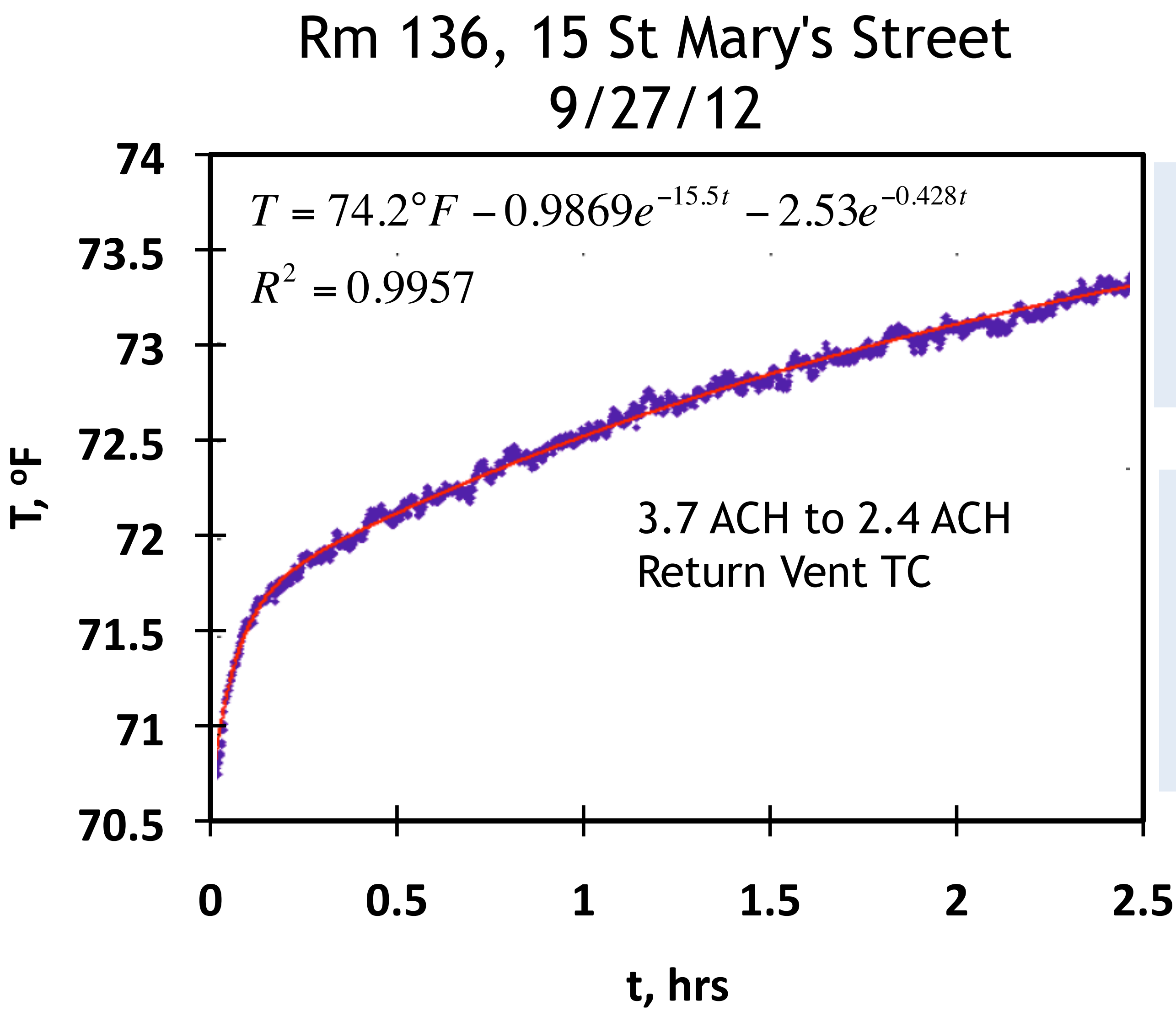
VERIFICATION OF 2^{ND} ORDER RESPONSE: EXPERIMENT



2^{nd} Order Response Fits Experimental Response

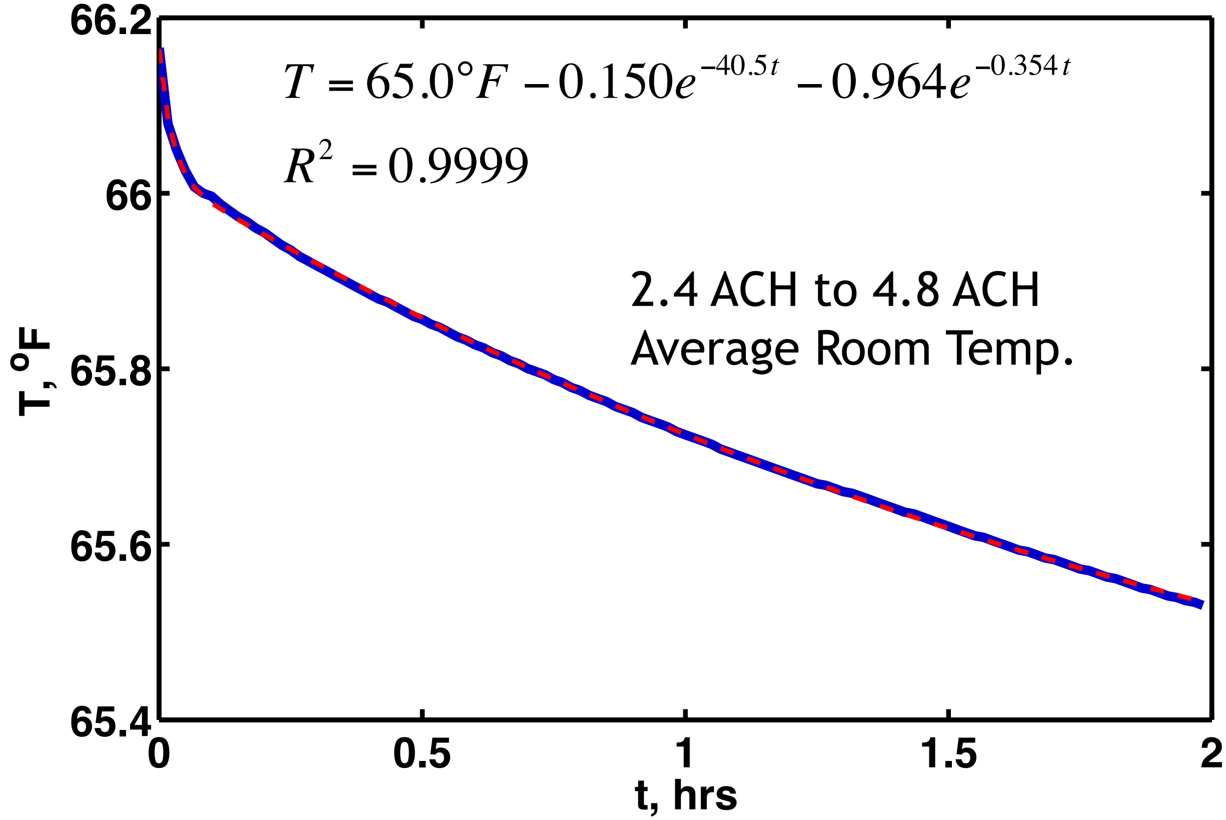
Model Captures Key Physics: Wall-Air Thermal Coupling

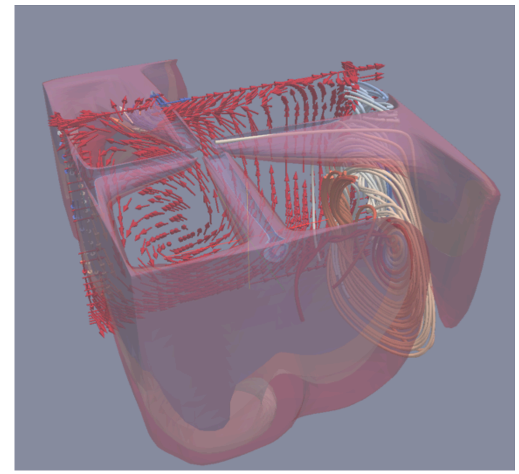
PROOF OF CONCEPT

VERIFICATION OF 2ND ORDER RESPONSE: CFD

CFD using OpenFoam

Model of Rm 136, 15 St Mary's Street





2nd Order Response also good fit for CFD

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PROOF OF CONCEPT

UNKNOWN PARAMETER EXPERIMENTS

Determined fit constants from test A

↓

Used known parameters

$ACH, \Delta ACH, C_A, C_W, T_S$

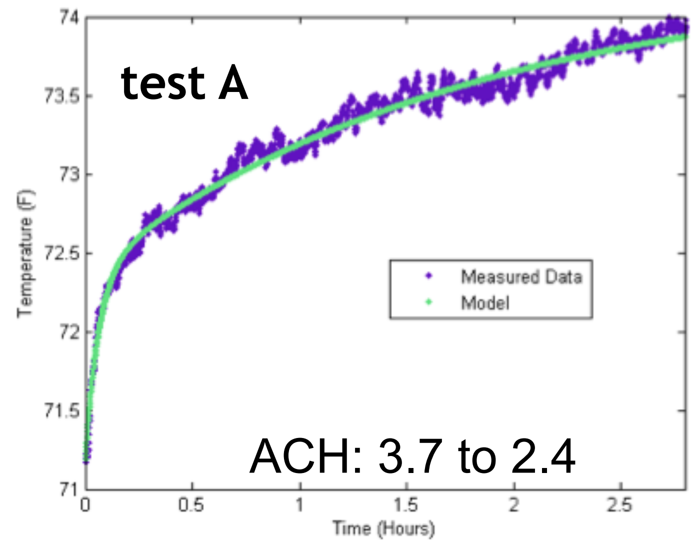
to estimate unknown parameters

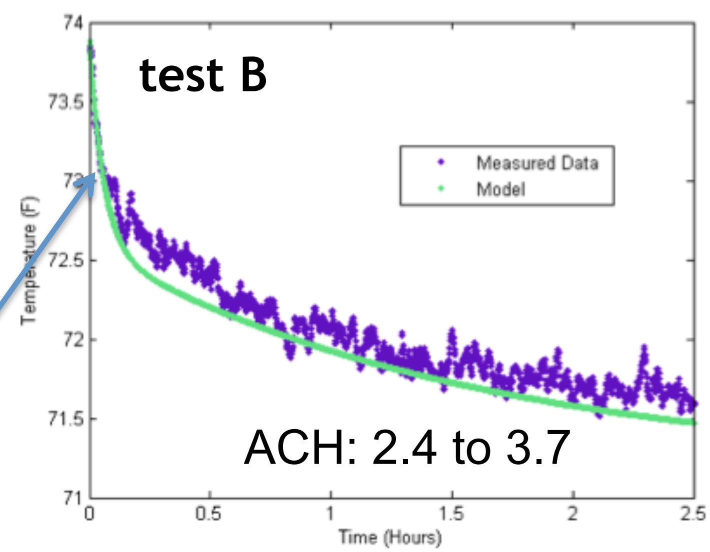
R_I, R_O, Q_I, T_∞

↓

Model w/ Full parameter set compared with test B

Initial Fast Response Well Predicted





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PROOF OF CONCEPT

SI TECHNIQUE: PARAMETER GROUPING

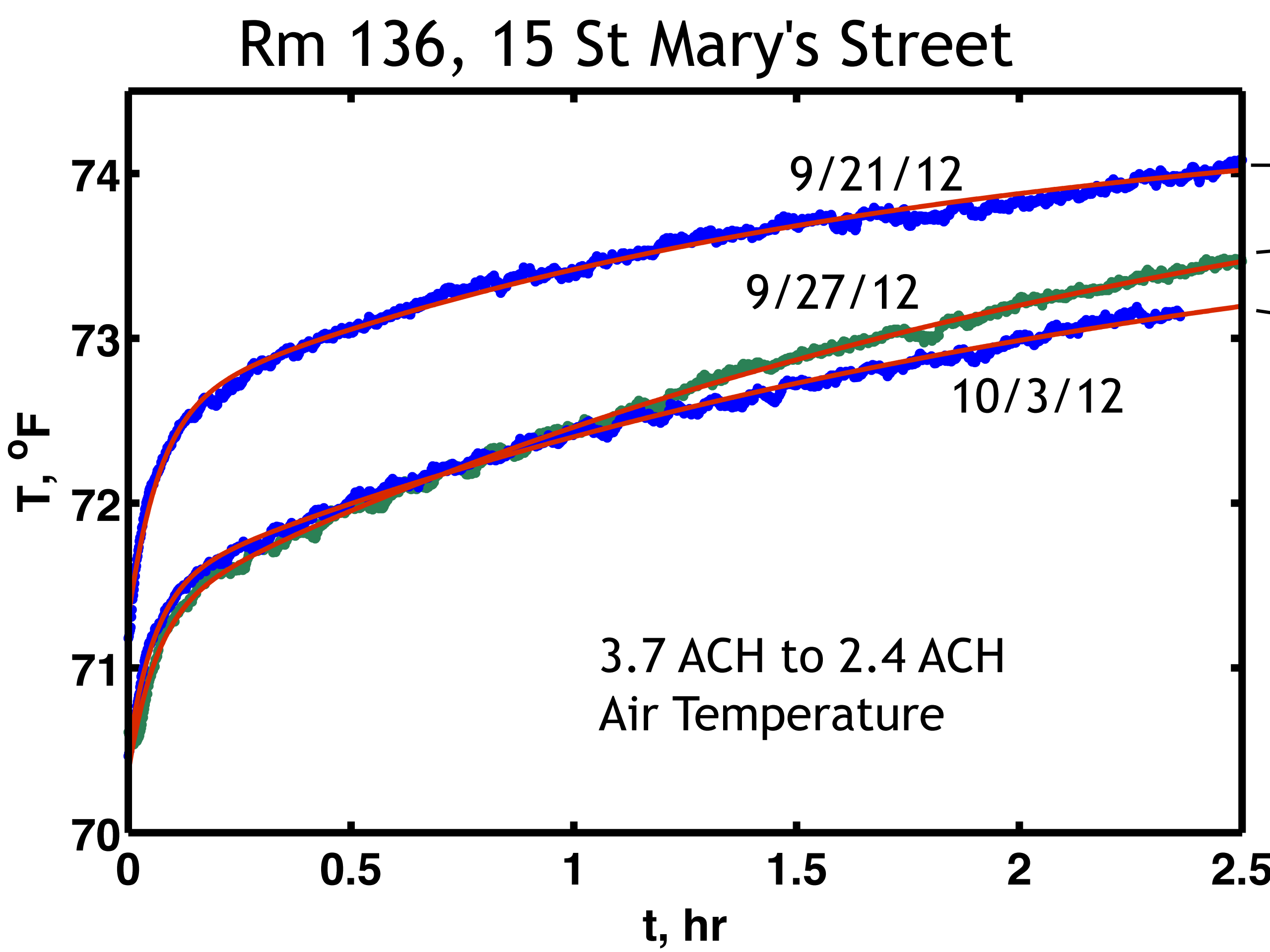
$$T_A = T_{A,SS} + \alpha_1 e^{\lambda_1 t} + \alpha_2 e^{\lambda_2 t}$$

$$\lambda_1, \lambda_2 = fn(a,\ b,\ c,\ d,\ T_{A,SS},\ T_{A,0})$$

$$\alpha_1, \alpha_2 = fn(\lambda_1,\ \lambda_2,\ a,\ c,\ T_S,\ T_{A,0})$$

$$a = \frac{1}{R_I C_W} + \frac{1}{R_O C_W} \qquad b = ACH \qquad c = \Delta ACH \qquad d = \frac{1}{R_I C_A}$$

ACH EXTRACTION: EXPERIMENT



−ΔACH	
SI value	Measured
1.35	1.3
1.25	1.3
1.33	1.3

Capture ΔACH within 5% for 3 trials

COMMERCIALIZATION OPPORTUNITY

Building Market: >100,000 sq. ft. with BAS

Building Segment	Size (Million Sq ft)	Potential Savings (Million $)**
M.U.S.H.*	6,222	622
Commercial	4,581	458

* Municipalities, Universities, Schools, Hospitals

** Based on average energy costs. Many cities have higher costs

- **Significant Market Opportunity**
- **Office buildings**
  - **Lower payback required**

COMMERCIALIZATION CHALLENGES

Aligning value offered with decision authority	**Start with Owner-Occupied Office Buildings**
Competitive and segmented landscape	**Differentiation** **Low Cost, Software-Based** **Low payback period** **Full Solution** **Upfront Analytics**
Accessing Markets	**Strategic Business Partnering** **ESCO– MUSH market**
New Untested Technology	**Strategic Technical Partnering** **_Building-Scale Demonstrations**

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COMMERCIALIZATION STATUS

aeolus
BUILDING EFFICIENCY

MIT CLEAN ENERGY PRIZE
AWARDED BY: NSTAR & THE U.S. DEPARTMENT OF ENERGY
2013 SEMI-FINALISTS

Boston University School of Management
Institute for Technology Entrepreneurship & Commercialization
New Venture Competition Finalists

AUTOMATED TECHNIQUE OF MEASURING ROOM AIR CHANGE RATES IN HVAC SYSTEMS
U.S. Provisional Patent Application No.: 61/561,131
International Application No.: PCT/US2012/065786

SUMMARY

- Room thermal dynamics follows 2nd order response based on air-wall thermal coupling
- SI/software approach for measuring ACH
- Proof of concept experiments on BU buildings
- Future work
  - Refine SI extraction approach
  - Integration with BAS
  - Large-scale testing & implementation

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